A STUDY OF THE DISTRIBUTION OF WEATHER ACCOMPANYING COLORADO CYCLOGENESIS [1]

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ABSTRACT

The distribution of weather with 21 cyclones which formed in the lee of the Colorado Rockies during the winter and spring of 1959 through 1963 is studied. The relation of the probability and form of precipitation and severe weather to circulation patterns (and their derivatives) at the surface and 500 mb. is shown from 12 hr. before cyclogenesis to 48 hr. after cyclogenesis. It is concluded that the weather models derived by this procedure are a useful starting point for weather forecasting, given predictions of 500-mb. flow and vorticity, vertical velocity, and surface pressure pattern.

1. INTRODUCTION

Several investigations of cyclogenesis in the lee of the North American Rockies are available in recent technical literature. Studies by Newton [1], Hage [2], and more recently by Schallert [3] to mention a few, have dealt with this problem from a combined theoretical-synoptic viewpoint. None of these papers described the distribution of weather during and after lee cyclogenesis. The Weather Bureau's Office of Forecast Development [4] did deal with the synoptic climatology of precipitation associated with all winter storms in the eastern two-thirds of the United States. Also, several studies [5], [6], [7] relating 500-mb. vorticity advection to weather occurrence have been completed in recent years.

In this paper we model the distribution of weather and its correlation with pressure patterns (and their derivatives) during early winter and spring cyclogenesis in the lee of the American Rockies. Practicing forecasters have come to recognize this type of storm as a producer of widespread severe weather [2] over much of the United States. For the purpose of this study we assume that an experienced meteorologist using available numerical prognoses can now make reasonably accurate 24- to 48-hr. forecasts of pressure distributions at the surface and aloft. Although this may be an optimistic assumption in some cases, the intention here is not to focus attention on prediction of pressure patterns. Nevertheless, we do recognize that the mean flow patterns derived in this study will be useful to the forecaster in his interpretation of numerical prognoses.

[1] Delivered at the 228th National Meeting of the American Meteorological Society, Washington, D.C., April 21-24, 1964.

[2] Severe weather is defined as including blizzards as well as heavy thunderstorms and tornadoes.

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2. SELECTION OF CASES

All 28 Lows which deepened in the vicinity of eastern Colorado and New Mexico during February, March, and April of 1959 through 1963 were considered for this study. This is the familiar area of Colorado cyclogenesis as discussed by Petterssen [8]. Not all of the 28 Lows were selected for study. Eliminated were seven cases in which a sharp trough or closed Low at 500 mb. moved across the southern Rockies and the accompanying surface storm center filled over the Plains and reformed to the southeast. These storms were usually associated with a split in the

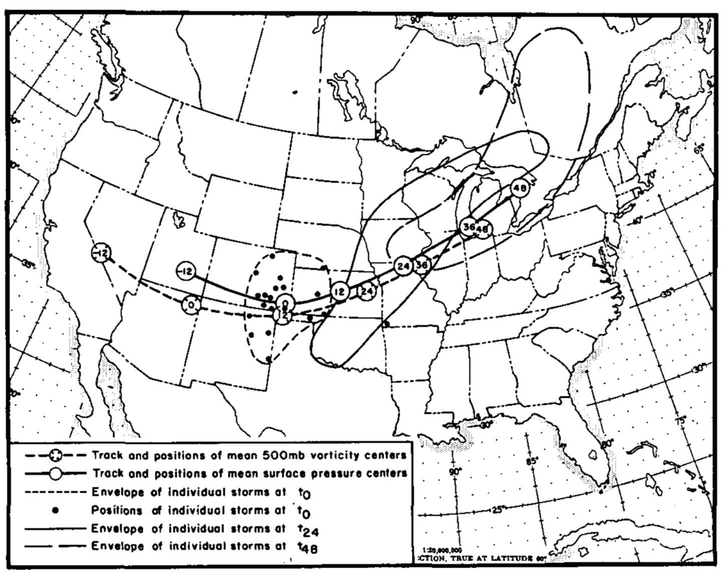

FIGURE 1.—Mean tracks of surface center and 500-mb. vorticity center for 21 storms which formed in lee of Colorado Rockies.

500-mb. flow and blocking surface High over eastern North America. Therefore, of the original 28 cases, 21 were selected in which the storm developed and moved generally northward and eastward. All but one of these cases are enclosed by the dashed line in figure 1. These correspond to the storms classified as Type A by Schallert [3] in his study of cases from November 1952 through March 1955.

The 21 storms selected for this study show good homogeneity of development and movement and can be considered as typical spring Colorado-type cyclones. Figure 1 shows the mean tracks of the surface pressure and/or vorticity center and the track of the 500-mb. vorticity center for the 21 cases. These mean positions were obtained by arithmetic averaging of the latitude and longitude of individual centers. The 21 surface centers are quite closely grouped in an oval about the cyclogenesis or t_0 position. However, the individual storm paths tend to stretch out along the mean path after initial time, indicating more variation in speed than direction of movement. For instance, in figure 1 the solid-line envelope encloses the spread of individual centers 24-hr. later, and the long-dashed-line envelope encloses all the center positions at 48 hr. At 24 hr. the fact that the mean surface position is skewed to the southwest in the envelope of all storms indicates that faster-moving storms were less frequent and farther north. The same is true at 48 hr.

3. TREATMENT OF DATA

Choice of the time and place of cyclogenesis, or t_0, was based on the change in slope of curves of surface absolute vorticity shown in figure 2a. Time t_0 was necessarily selected as 0000 GMT or 1200 GMT because of the availability of upper-air data at those times. Surface pressures and 500-mb. heights were recorded for all grid points shown in figure 2b for each of the 21 storms in 12-hr. intervals from t_{-12} through t_{+48}. To record all data, the grid as shown was centered on the position of the surface center with the central column (No. 7) parallel to the meridian through the surface Low. Also, the occurrence of precipitation as predominant weather was recorded for each of the 41 interior grid-point areas surrounding the storm center and within the area bounded by a dashed line in figure 2b. Precipitation was considered as being predominant when reported by more than 50 percent of the stations in a given area at or within one hour of observation time. Type of predominant precipitation was also recorded for each area. NWP 600-mb. vertical-motion values were then tabulated for the 41 interior points. Using the tabulations just described, three mean charts were derived for each 12-hr. period, from t_{-12} through t_{+48} (figs. 3 through 8). In the upper-left panel of each figure is the mean sea level pressure chart with the 1000 to 500-mb. thickness field superimposed. The heavy solid line is the averaged position of the line of separation of snow and rain for all storms and was located on this chart from the summaries of predominant type of precipitation. The lower-left panel contains the 500-mb. flow chart and 500-mb. relative geostrophic vorticity analysis. The mean position of the jet core for this time is shown as a heavy-arrowed line estimated from the spacing of mean contours. The third panel, in the upper-right of each figure, contains an analysis of mean NWP 600-mb. vertical motions [3] and of the percentage frequency that the predominant weather is precipitation at, or 1 hr. before, the time of the figure. For purposes of orientation, the surface low center (crossed circle), 500-mb. vorticity maximum (solid circle), 500-mb. jet (heavy arrows) and two 500-mb. contours are also shown on this last chart.

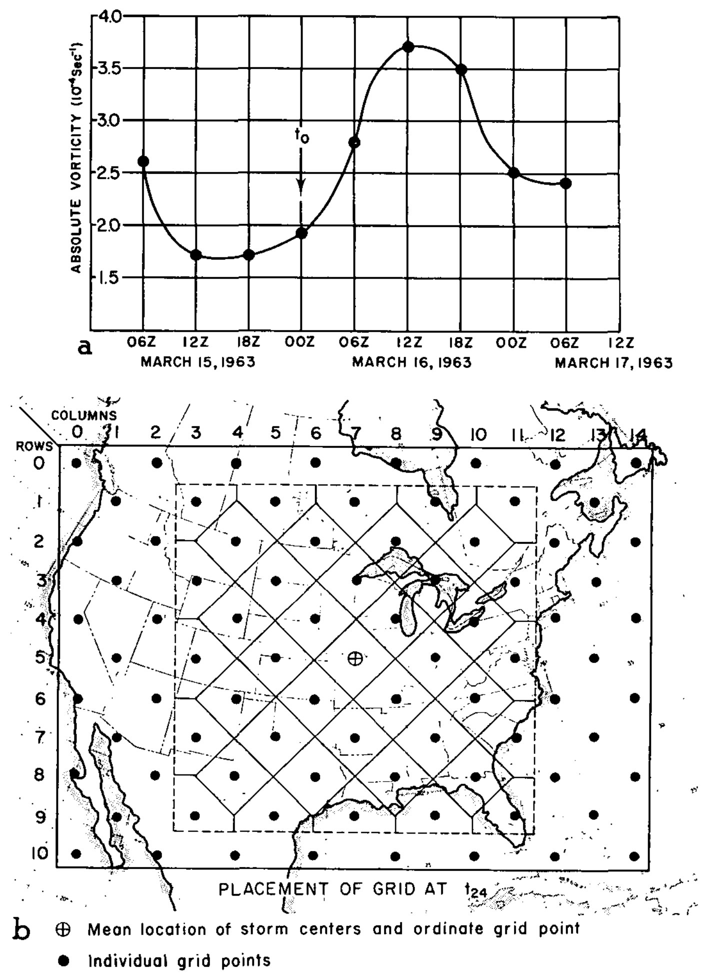

FIGURE 2.—(a) Sample of method of defining time and place of cyclogenesis, t_0. (b) Grid used for tabulation of data. Individual, rather than mean centers, were used when data were tabulated. All (83) grid points were used for surface and 500-mb. charts; interior (41) for weather tabulations.

4. DISCUSSION OF RESULTS

Consider first the situation 12 hr. before cyclogenesis

[3] Vertical motions were computed using the NMC operational 2-level "Mesh Model" in 1959 through 1962. In 1963 the vertical velocities used were computed from the 3-level operational baroclinic model.

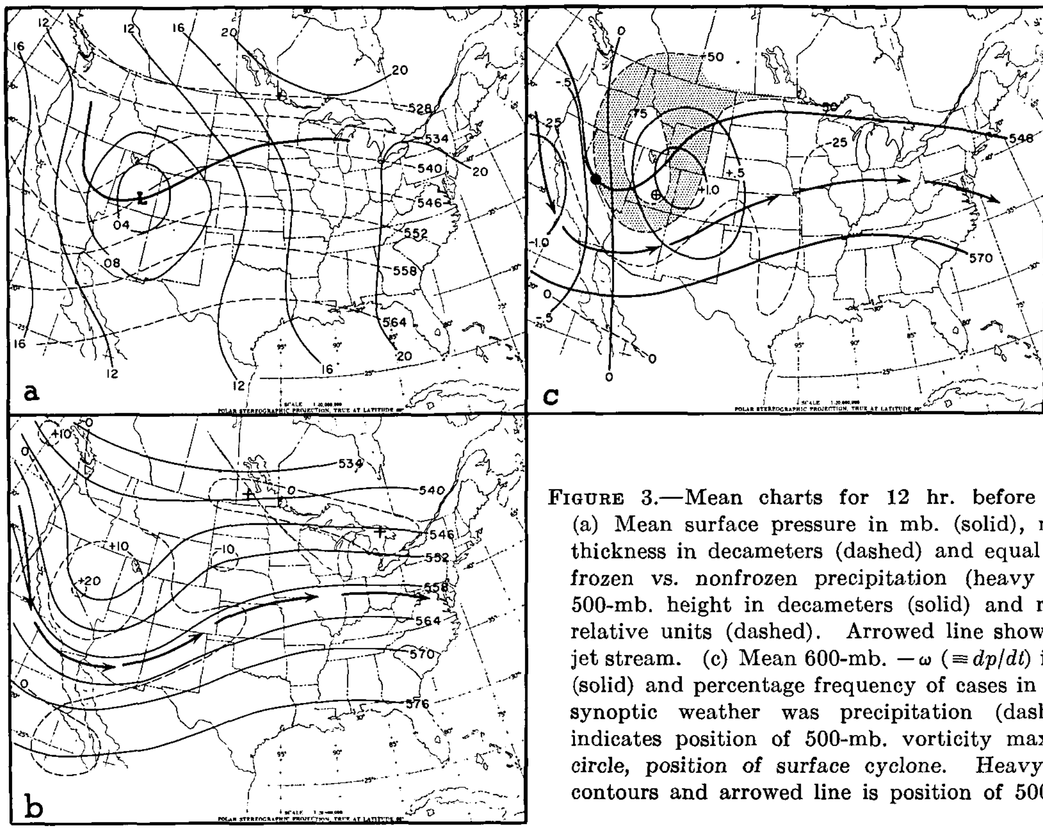

Figure 3.—Mean charts for 12 hr. before cyclogenesis (t_{-12}). (a) Mean surface pressure in mb. (solid), mean 1000–500-mb. thickness in decameters (dashed) and equal probability line of frozen vs. nonfrozen precipitation (heavy solid). (b) Mean 500-mb. height in decameters (solid) and relative vorticity in relative units (dashed). Arrowed line shows mean position of jet stream. (c) Mean 600-mb. $-\omega$ ($\equiv dp/dt$) in mb. sec.$^{-1}$ $\times$ 10^{-3} (solid) and percentage frequency of cases in which predominant synoptic weather was precipitation (dashed). Solid circle indicates position of 500-mb. vorticity maximum and crossed circle, position of surface cyclone. Heavy lines are 500-mb. contours and arrowed line is position of 500-mb. jet from (b).

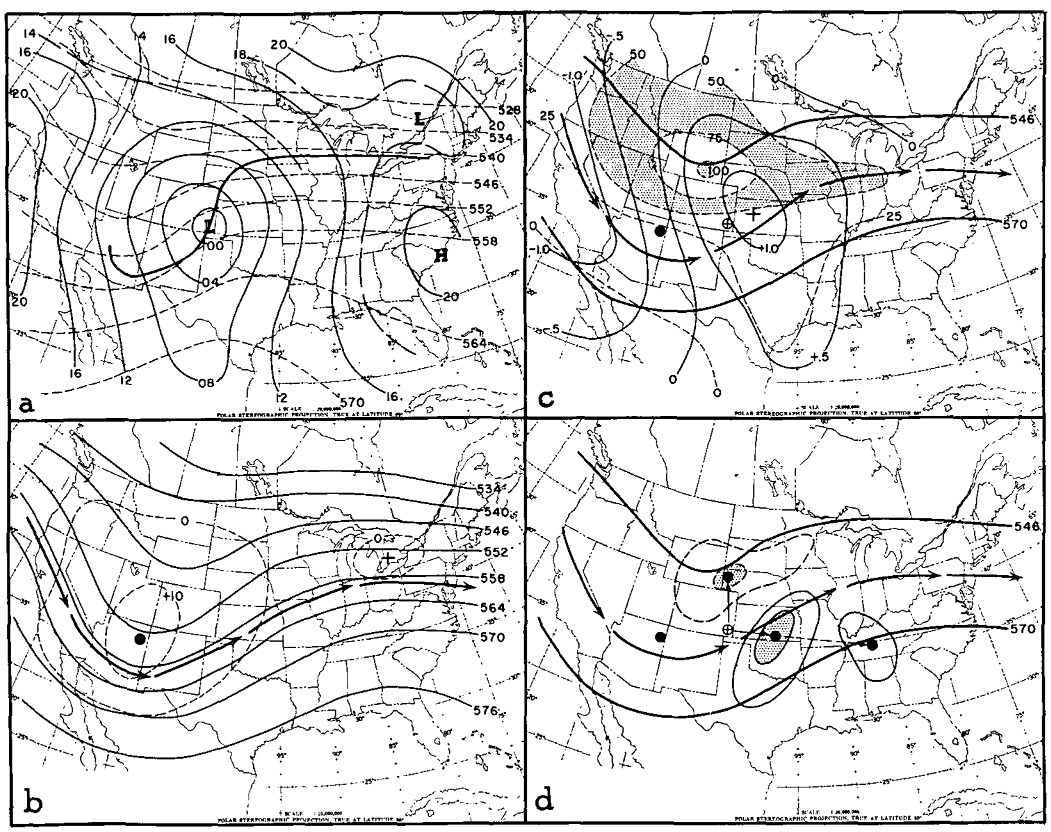

Figure 4.—Mean charts for time of cyclogenesis (t_0). (a), (b), and (c) are same as in figure 3. (d) Outer dashed line encircles all observed areas of heavy snow in 12 hr. after t_0; inner dashed line and stippling show mean size and position of heavy snow in 12 hr. after t_0. Both curves given in relation to mean position of surface low (crossed circle). Solid curves give a similar analysis of occurrences of severe thunderstorm activity.

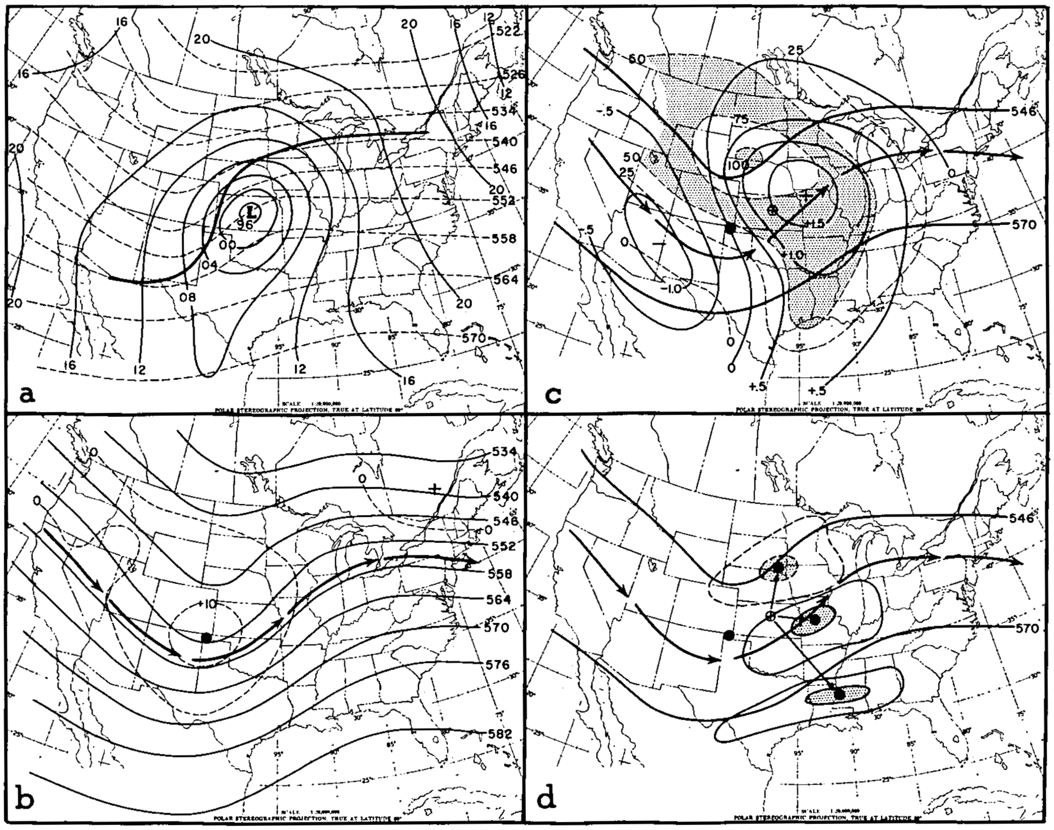

FIGURE 5.—Mean charts for time of cyclogenesis plus 12 hr. (t_{+12}).

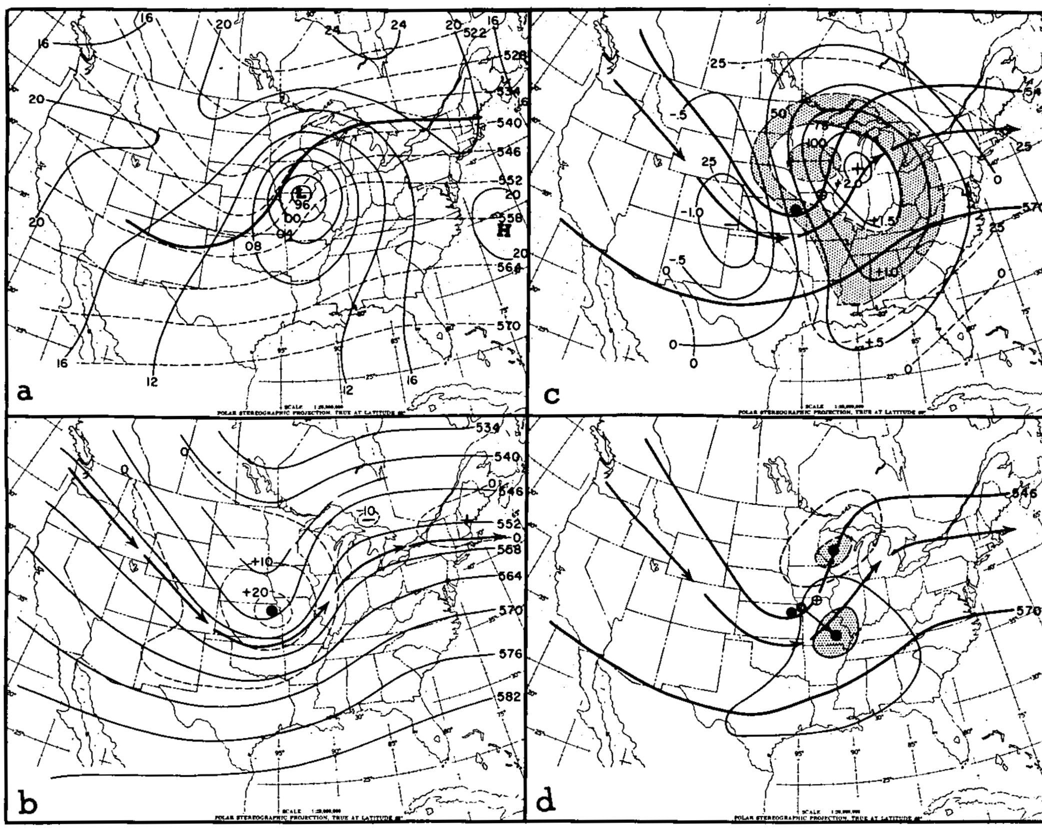

FIGURE 6.—Mean charts for time of cyclogenesis plus 24 hr. (t_{+24}).

(fig. 3). The surface Low is located in southeastern Utah about 5° of latitude east of the 500-mb. vorticity maximum. The 500-mb. jet is well south in the trough dipping to about 32° N. The important feature which distinguishes a spring storm of this type is the amplitude of the 500-mb. trough as it crosses the southern Rockies. The individual 500-mb. charts resemble this chart very closely. As pointed out in section 2, seven storms were eliminated because the associated 500-mb. troughs were of noticeably greater amplitude as they crossed the southern Rockies.

The maximum probability of precipitation at this time, 12 hr. before cyclogenesis, is centered just west of Great Salt Lake. This position lies about 4° of latitude northwest of the surface center and about 4° of latitude west-northwest of the maximum upward vertical motion. The maximum equivalent barotropic upward vertical velocity as indicated by the strongest 500-mb. positive vorticity advection (over eastern Utah in fig. 3b) bears a relation to the probability of precipitation similar to that of the baroclinic vertical motion computations in figure 3c. In figure 4 for time t_0 parts a, b, and c are similar to those of figure 3. The fourth panel (4d) gives a mean chart of heavy snow, defined as 4 in. or more in 12 hr., and severe thunderstorm activity, as defined by criteria of the Weather Bureau's Severe Local Storms unit at Kansas City,[4] for the 12-hr. period following t_0.

The heavy snow analysis was made using 6-hr. precipitation charts and 3-hourly surface analyses. Heavy snow was assumed to have occurred where 0.4 in. or more of precipitation in the form of snow was reported in 12 hr. Analyses of these areas were then related to the mean position of the surface Low. The area of the heavy snowfall was measured with a planimeter and its average size and position determined in relation to the surface center. The average area and position of heavy snow during the 12 hr. after t_0 is indicated in figure 4d by the stippled area. The surrounding dashed line encloses all areas of heavy snow observed during this period, and can therefore be considered as a measure of the scatter about the mean area.

A similar analysis was conducted for severe thunderstorm activity (shown by the stippled area and surrounding solid curve in figure 4d). The data source for severe thunderstorm activity was the Kansas City Severe Thunderstorm Log.

In the mean patterns at t_0, the surface Low is positioned 6° of latitude downstream from the 500-mb. vorticity maximum which is somewhat weaker than in figure 3a (t_{-12}). The relations between the precipitation and vertical motion, and the surface center and 500-mb. vorticity maximum are similar to those 12 hr. earlier. The cold frontal trough to the south of the Low over western Texas remains fairly dry. The mean position of the influx of Gulf moisture is suggested by the dip southward over eastern Texas of the 25 percent isoline of precipitation occurrence (fig. 4c). Of the storms investigated 75 percent were associated with heavy snow in the 12-hr. period after t_0. The mean position of heavy snow is centered 4.5° of latitude north-northwest of the surface center in the Nebraska panhandle region. The mean area is elliptical in shape and covers about 18,000 sq. mi. Beginning with t_0, the mean heavy snow area lies on the cold side of the 5540-m. 1000- to 500-mb. thickness line which is in effect the equal probability line of rain and snow.

There were 83 reported occurrences of severe thunderstorm activity in the 12 hr. following t_0 of which 82 percent occurred within the solid curve centered in the Kansas-Oklahoma area, and 17 percent within the solid curve centered in Tennessee. There were no reports of severe thunderstorms in 10 of the 21 storms during this period. The stippled area over Kansas represents the mean size, shape, and position of the area in which severe thunderstorms occurred. This lies just to the right of the 500-mb. jet stream and 4° of latitude east of the surface Low.

By t_{+12} (fig. 5) the mean position of the surface Low is in central Kansas and the intensity is markedly greater. The slope between the Low and the mean 500-mb. vorticity maximum has decreased to 4° of latitude—a reflection of the occlusion process associated with development.

The equal probability line of frozen vs. non-frozen precipitation fits Wagner's [9] data very well since it lies close to the 5540-m. thickness contour east of the mountains. In spite of the strong geostrophic warm advection to the north and east of the low center, this rain-snow line has changed very little in position since t_0, evidence of cooling resulting from the strong rising motion and evaporation in this quadrant of the storm.

Little change is shown in the relationship between the position of the maximum probability of precipitation and the vertical motion, surface center, and 500-mb. vorticity maximum. However, the probability of precipitation in the area ahead of the cold frontal trough does show an important increase. This results from a combination of Gulf moisture and the rising motions in advance of the front.

The statistics relating to heavy snow and severe weather (fig. 5d) are: (1) Heavy snow was associated with 75 percent of the storms. (2) Severe thunderstorm activity occurred with 62 percent of the storms for a total of 141 reports. (3) 77 percent of the thunderstorms occurred in the area east of the surface Low, 21 percent in a secondary area southeast of the Low. The mean position of the former area is again just to the right of the 500-mb. jet stream.

At t_{+24} (fig. 6) the storm reaches peak intensity at both 500 mb. and the surface. The slope between the surface and 500-mb. vorticity maximum has decreased to 3° of latitude as the storm is at this time fully occluded.

The peak in storm intensity is reflected in the intensities of vertical motions and frequency of severe weather. Heavy snow was observed in 84 percent of the storms, the highest percentage for any of the 12-hr. periods

[4] Severe thunderstorm criteria include reports of tornadoes, funnel clouds, wind gusts of 50 kt. or greater, and hail of ¾ in. or greater.

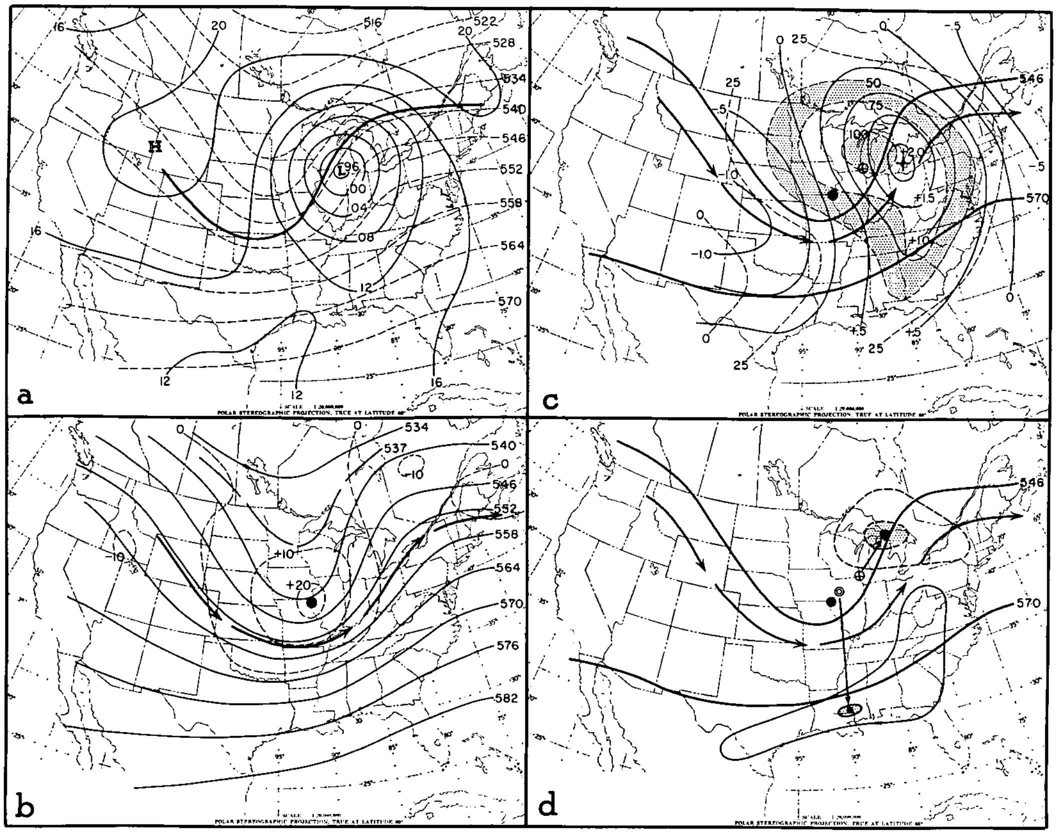

FIGURE 7.—Mean charts for time of cyclogenesis plus 36 hr. (t_{+36}).

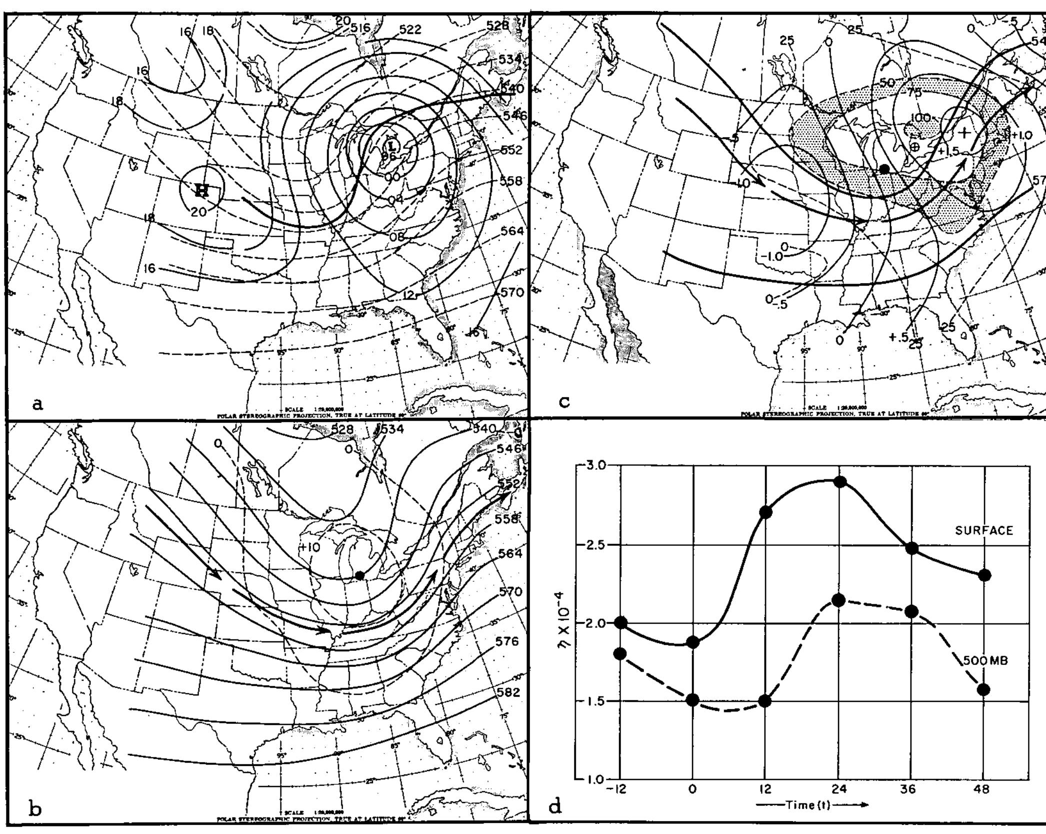

FIGURE 8.—Mean charts for time of cyclogenesis plus 48 hr. (t_{+48}). (a), (b), and (c) are same as in figure 3. (d) Surface and 500-mb. absolute vorticity maxima from t_{-12} through t_{+48}.

studied. Severe thunderstorm activity was observed in 81 percent of the storms, with a total of 150 occurrences. Since 127 of these severe thunderstorms occurred with six storms, the mean surface center position of these storms is the one used in figure 6d to show the relation to the mean position of the severe thunderstorm area which again lies just to the right of the 500-mb. jet.

The six storms involved with four-fifths of the severe weather occurrences were investigated to see if they separated in some fashion from the 21 cases studied. Five of the six storms were found to have tracks on or south of the mean track shown in figure 1. Thus, these storms were closer than average to the main moisture source in the Gulf of Mexico.

At t_{+36} (fig. 7), the surface Low is located near Chicago, 4° of latitude downstream from the 500-mb. vorticity maximum. The location of the equal probability line of frozen vs. non-frozen precipitation continues to fit Wagner's data well and has changed in position very little to the northeast of the Low in spite of the indicated geostrophic warm air advection.

The relation between vertical motion and probability of instantaneous precipitation is similar to that of t_{+24}. Heavy snow was observed in 77 percent of the storms. A sharp decrease in severe thunderstorm activity is noticeable at t_{+36}; it was reported in only 12 storms. There were only 44 occurrences, two-thirds of which are within the large area enclosed by the solid line. The remaining one-third are well scattered outside this area. The shape of this area suggests the important role of the cold front in severe thunderstorms during this period.

At t_{+48} (fig. 8) the number of severe thunderstorm reports dropped to 31 which were so widely scattered that no analysis was performed. A heavy snow analysis was omitted because of lack of sufficient data in southeastern Canada. In figure 8 the relationship between vertical motion and precipitation is similar to that in existence throughout the history of the storm although there is some tendency for precipitation to hang back over the Great Lakes. The cold frontal trough accelerates eastward and dries out considerably during this period, since the 50 percent line of precipitation occurrences recedes northward about 5° of latitude. These events accompany secondary cyclogenesis which occurred off the Virginia Capes in several of these storms.

5. SUMMARY

The primary results of this study are illustrated in figure 8d and figure 9. The graph in figure 8d gives a plot of the surface and 500-mb. absolute vorticity maxima from t_{-12} through t_{+48}. The most rapid development at the lower level occurs between t_0 and t_{+12} and maximum intensity is reached at t_{+24}. At 500 mb. a decrease in intensity is observed as the trough passes over the southern Rockies followed by a sharp increase between t_{+12} and t_{+24}. This lags the low-level mountain-induced cyclogenesis by 12 hr. As at the surface, maximum circulation intensity at 500 mb. occurs at t_{+24} with decreasing intensity thereafter.

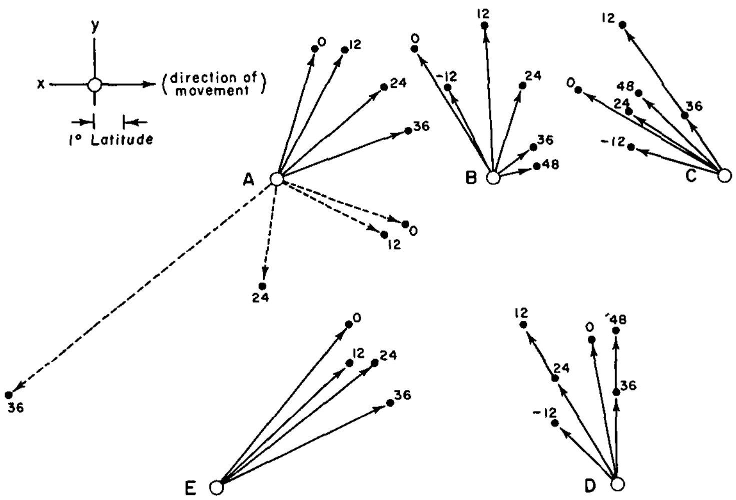

FIGURE 9.—Summary of relation of precipitation and severe weather to pressure patterns and their derivatives. x–y coordinates give orientation of axes along direction of movement of the storm for all diagrams; (A) relation of mean heavy snow areas (t_0 through t_{+36}) to position of surface Low given by solid vectors, and relation of mean area of severe thunderstorm activity (t_0 through t_{+36}) to position of surface Low by dashed vectors; (B) relation of maximum probability of instantaneous precipitation to position of surface center; (C) relation of maximum probability of instantaneous precipitation to baroclinic vertical velocity; (D) relation of probability of instantaneous precipitation to center of maximum positive vorticity advection; (E) relation of mean heavy snow area to 500-mb. vorticity maximum.

The solid vectors of plot A (fig. 9) show the shift in position with time of the mean area of heavy snow in relation to the surface Low. The mean area at all times is about 4° of latitude from the low center but rotates clockwise from t_0 to t_{+36}. This shift is undoubtedly a consequence of the gradual cooling of the storm as it occludes and moves northward, as well as of the fact that the highest probability of heavy snow lies close to the snow vs. rain equal probability line where the moisture content of the air is higher.

The lower vectors of plot A show the shift in time of the severe thunderstorm activity. At t_0 the storm is wave-like with a large warm sector composed of a dry layer of air from the southern Rockies, in many cases superimposed on a moist layer from the Gulf. The clockwise shift and lengthening with time of the vectors results from the occlusion process and consequent "pinching-off" of the warm sector.

Plot B (fig. 9) shows the change in position with time of the area of maximum probability of instantaneous precipitation in relation to the surface Low. This area shifts from northwest to northeast of the surface Low and the distance from the Low decreases. This characteristic can be explained by the following circumstances:

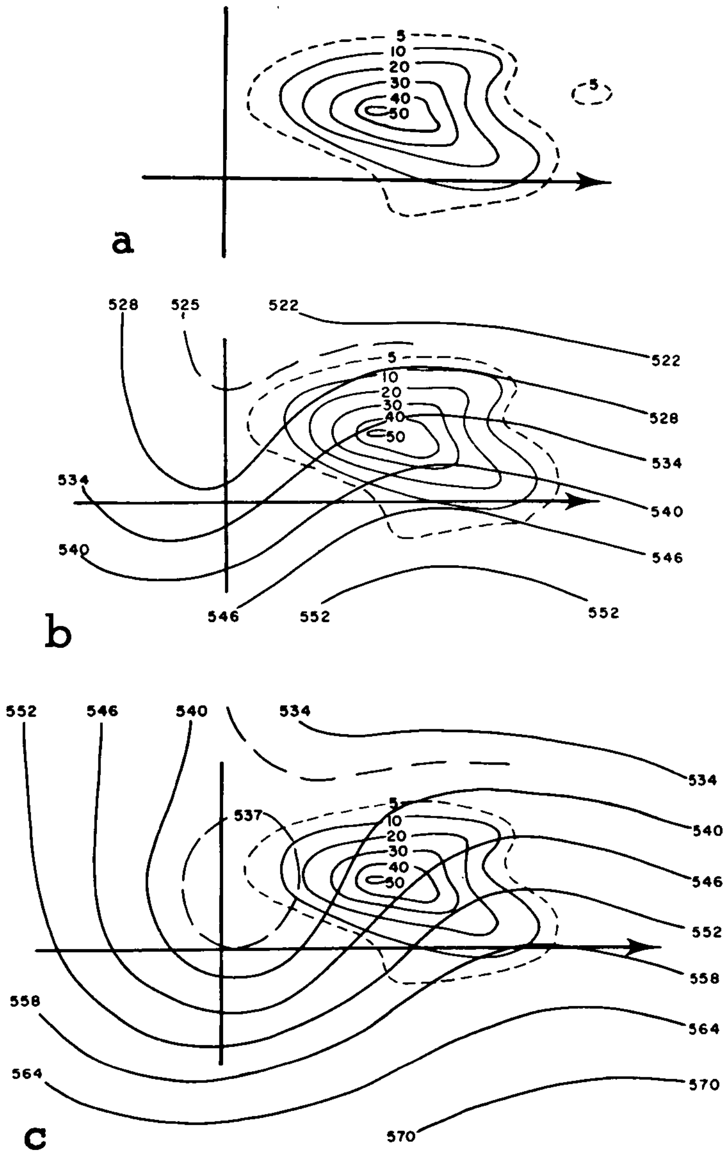

FIGURE 10.—Synoptic climatology of heavy snow over United States east of 105th meridian during winter of 1963–64 showing percent frequency of occurrence of heavy snow (a) with respect to the initial 500-mb. vorticity maximum and the direction of movement of the vorticity maximum during the following 12 hr.; (b) in relation to 1000–500-mb. thickness pattern; (c) in relation to 500-mb. flow patterns.

1. During the early history of the storm, the moisture source is the Pacific Ocean while in later stages the Gulf of Mexico serves as the source.

2. The warm air feeding into the storm at low levels from the south at t_{-12} through t_{+12} is on the average relatively dry. Therefore, condensation does not occur until the air has been subjected to rising motion for a longer than normal time. This evidently happens after the air has circulated around the Low into the northern and northwestern quadrants of the storm.

3. The terrain-induced upward motion is at a maximum north-northwest of the Low at t_0 and t_{+12}.

Plots C and D (fig. 9) show the relationship with time of the area of maximum probability of instantaneous precipitation with the center of 3-level model vertical velocity and the center of equivalent barotropic vertical velocity respectively. Both models serve equally well in specifying instantaneous precipitation, suggesting that in this type of storm little is to be gained by additional resolution in the vertical, in the calculation of macroscale vertical motion. Note that the highest probability of precipitation is not with the maximum of rising motion, as calculated by the barotropic or baroclinic models, but is about 4° of latitude northwest of this maximum.

Plot E (fig. 9) shows the relationship between the 500-mb. vorticity maximum and heavy snow in the subsequent 12 hr. As can be seen from the small scatter of the vectors the position of the 500-mb. vorticity maximum alone is extremely useful in the prediction of heavy snow for the next 12 hr. Throughout the history of these storms, it is interesting to note (1) the persistent association of the mean heavy snow area with the 5540-m. thickness line and (2) the lack of variation with time in the location of this 5540-m. thickness line for a distance of 10° of latitude ahead of the surface center. These two relations indicate that the latest thickness analysis can be used as a guide in locating the most likely area of heavy snow during the following 12 hr.

At this point it is appropriate to inquire if the relationships between weather and circulation patterns typical of these Colorado storms can be generalized to other winter storms. Synoptic experience and climatology suggest that as far as severe weather is concerned, the Colorado storms are not typical. However, a recent study by Paul Goree, of NMC, relating circulation patterns to all occurrences of heavy snow during the 1963–64 season in the United States and southern Canada east of the 105th meridian disclosed relationships very similar to those presented in this study. The results of Goree's investigation are shown in figure 10 [6] and can be compared with mean heavy snow areas in figures 4, 5, 6, and 7.

6. CONCLUSION

Modeling of this type is not offered as a solution to the weather forecast problem. However, it should be a useful starting point for the weather forecast once guidance predictions of 500-mb. contours, 500-mb. vorticity, vertical velocity, surface pressure patterns, etc., have been received at the field station via facsimile. The forecaster's job is to improve on the weather models. This involves noting the similarities and differences between the current charts and the mean charts of this study, and interpreting what the similarities and differences mean in terms of modifications to the mean weather models.

[6] Taken from NMC/Analysis and Forecast Division Office Memorandum No. 38–64, "Heavy Snow During the 1963–64 Season," November 2, 1964.

ACKNOWLEDGMENTS

We wish to express our appreciation to Messrs. Ronald Lofgren and Stephen Graw, summer-student employees at NMC, who did most of the data tabulation involved in this study. We also are indebted to the following employees of the Analysis and Forecast Division of NMC; Mrs. Mildred Matthews, who performed the data summarizations; Mr. Joseph Mullaney, who drafted the figures for this article; and Mrs Beatrice Durkin who assisted with the manuscript.

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[Received December 11, 1964; revised February 5, 1965]

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